DYNAMIC CHARACTERISTICS OF WOODFRAME BUILDINGS

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ABSTRACT

The dynamic properties of wood shearwall buildings were evaluated, such as modal frequencies, damping and mode shapes of the structures. Through analysis of recorded earthquake response and by forced vibration testing, a database of periods and damping ratios of woodframe buildings was developed. Modal identification was performed on strong-motion records obtained from five buildings, and forced vibration tests were performed on a two-story house and a three-story apartment building, among others. A regression analysis is performed on the database to obtain a period formula specific for woodframe buildings. It should be noted that all test results, including the seismic data, are at small drift ratios (less than 0.1%), and the periods would be significantly longer for stronger shaking of these structures. Despite these low amplitudes, the equivalent viscous dampings for the fundamental modes were usually more than 10% of critical during earthquake shaking.

Introduction

Current building codes prescribe a design earthquake load based on the characteristics of the building and site under evaluation. These codes specify simplified formulas to approximate a building's fundamental period, which can help describe how it will behave during an earthquake. Recent research has shown that the 1997 Uniform Building Code period formulas substantially underestimate the fundamental periods for concrete and steel moment-resisting frame buildings, as well as those for concrete shearwall buildings (Goel and Chopra 1997, 1998). An important objective of this research is to evaluate and improve upon the current code period formulas for woodframe structures.

Much research has been done on the dynamic and cyclic characteristics of wood subsystems and connection panels, but full-scale testing of woodframe buildings had been sparse until the CUREE-Caltech Woodframe Project (CUREE 2001). A database of periods, dampings and mode shapes of woodframe buildings has been obtained under Task 1.3.3 of this project; this was accomplished by analyzing available seismic data and performing forced vibration tests. A

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period formula specific for woodframe structures is obtained by regressing on appropriate structural characteristics using this database, providing a descriptive parameter for the dynamic behavior of these buildings.

Available Seismic Records

Eight sets of earthquake records were obtained from five woodframe buildings instrumented by the California Strong Motion Instrumentation Program. The earthquake data were analyzed using the Caltech program MODE-ID, which uses a well-established system identification procedure to estimate the modal parameters of the dominant contributing modes for the building being evaluated (Beck 1978, Beck and Jennings 1980). The periods and dampings obtained are summarized in Table 1.

Table 1. Summary of building dynamic characteristics from earthquake records.

Building Location		**San Bernardino**			**Parkfield**		**Bishop**	**Indio**	**Eureka**
Building Height (top of roof)		29.9’			13.2’		17’	13.7’	26.0’
No. of Stories		3			1		1	1	2
Building Type		Motel			School		Fire-Station	Hospital	Office
Length:	**(Longit.)**	180.5’			48’		62’	298’	80’
	(Transv)	132’			30’		50’	148’	54’
Date of Earthquake		6/28 1997	7/26 1997	3/11 1998	4/4 1993	12/20 1994	5/17 1993	7/25 1997	2/8 1995
Magnitude (M_L)		4.2	3.7	4.5	4.2	4.7	6.0	4.9	3.9
Peak Roof Acceleration		9.2%g	7.8%g	7.1%g	12.3%g	20.1%g	4.4%g	8.2%g	6.2%g
Total Drift (mm):	**(Longit.)**	0.7	0.7	0.8	0.5	0.9	1.2	0.4	0.4
(Roof w.r.t. Base)	**(Transv)**	0.6	0.7	0.7	0.5	1.5	0.3	0.2	0.5
Periods (sec):	**(Longit.)**	0.22	0.20	0.23	0.14	0.15	0.11	0.13	0.17
(First Mode)	**(Transv)**	0.19	0.21	0.18	0.11	0.13	0.18	0.14	0.20
Frequency (Hz):	**(Longit.)**	4.6	5.0	4.4	7.3	6.6	8.7	7.9	5.8
(First Mode)	**(Transv)**	5.4	4.8	5.6	8.7	8.0	5.6	7.1	4.9
Damping Ratio:	**(Longit.)**	13.6 %	14.1 %	7.7 %	11.6 %	10.8 %	12.2 %	8.9 %	16.5 %
(First Mode)	**(Transv)**	17.3 %	6.9 %	11.7 %	14.2 %	15.3 %	7.0 %	6.3 %	14.9 %

The high damping levels from the modal identification of the seismic records are consistent with the damping levels exhibited in the shaking table tests of a 2-story woodframe house performed at the University of California at San Diego (Fischer et. al. 2001). The fundamental frequency estimates from different earthquakes for buildings with multiple earthquake recordings are quite consistent, since the drifts are at similar levels. (It is known from experience that the uncertainty in the estimates of the fundamental frequencies is relatively small if the drift levels are comparable from test to test.) On the other hand, the fundamental damping estimates vary significantly for the San Bernardino 3-story motel. This may be partly because the instrumentation layout does not allow the excitation of the structure to be well captured. However, experience has shown that the uncertainty in the damping estimates is relatively large even when the excitation is well defined; it is thought that this is partly because the assumed linear viscous damping is not a good model for the actual damping mechanisms and partly because the seismic response of the model is not very sensitive to changes in the damping level, and therefore the error measure in the program MODE-ID is more sensitive to frequency than to damping. The damping ratios for the model averaged 11.8% and ranged from 6.3% to 17.3% during earthquake shaking of the five buildings.

Detailed analysis of the earthquake records showed a gradual elongation in the natural periods of vibration over each record, which was longest at the time of strongest shaking and which gradually returned to the original value. Similarly, the damping ratios gradually increased during the course of the earthquake and were highest at the time of strongest shaking, after which they gradually returned to their original values. See Fig. 1 for a plot of the detailed analysis results for the 1-story Bishop fire-station.

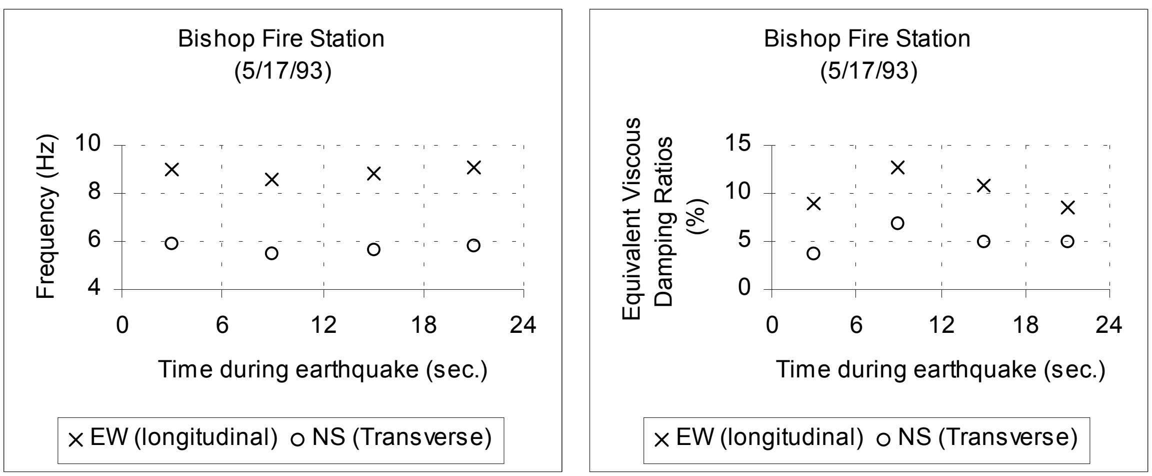

Figure 1. Bishop fire station MODE-ID analysis details. Note that peak earthquake shaking occurs within 6-12 second window.

Forced Vibration Tests

The forced vibration tests were performed to supplement the dynamic characteristics database, since currently only a limited number of earthquake records have been obtained in woodframe buildings. These tests measured harmonic vibrations induced by a shaking machine in the buildings being tested. The force delivered by the shaking machine is generated by the centrifugal acceleration of the weights, so it is proportional to the square of the frequency of rotation of these weights and also to their eccentricity around the rotating shafts (see Fig. 2).

Figure 2. Harvey Mudd College shaker: detail of shaft with weights at 2.5% eccentricity

Ranger seismometers and/or force balance accelerometers were used for recording the building response at each driving frequency, then sinusoidal curves were fitted to the recorded time histories from each output channel in order to determine their amplitude and relative phase. Only seismometer results are presented here. After calculating the frequency-response curves for all data channels, the modal frequencies and corresponding damping ratios were computed by using a curve-fitting approach involving nonlinear least-squares matching of the model and measured frequency response amplitudes. Results are shown in Table 2 for a 3-story apartment building and a 2-story house.

Table 2. Summary of building dynamic characteristics from forced vibration tests.

Building Location		**Catalina Ave., Pasadena**			**Del Mar Blvd., Pasadena**		
Building Height (top of roof)		20’			30’ (above garage)		
No. of Stories		2			3 + garage		
Building Type		House			Apartments		
Peak Total Drift (mm): (Roof w.r.t. Base)		0.54			0.52		
Shaking Direction	**Shaker Eccentricity**	**Period (Sec)**	**Freq (Hz)**	**Damp. (%)**	**Period (Sec)**	**Freq (Hz)**	**Damp. (%)**
NS (Longitudinal)	**2.5%**	0.175	5.7	5.0%	0.189	5.3	4.7%
	10%	--	--	--	0.192	5.2	4.6%
	20%	--	--	--	0.196	5.1	4.9%
EW (Transverse)	**2.5%**	0.182	5.5	2.9%	0.227	4.4	4.7%
	10%	0.196	5.1	2.9%	--	--	--
	20%	0.204	4.9	2.7%	0.238	4.2	5.1%

2-Story House (Pasadena)

This two-story house, owned by the California Institute of Technology and located in the vicinity of the campus, was being used as an undergraduate dormitory. It is built on cripple walls, and constructed circa 1940, with first floor plan area nearing 2000 square feet. It has two brick fireplaces, which have been seismically retrofitted and anchored to the roof. The building has wood shingle siding, the interior finish is plaster, and the original hardwood floors are still in place. The shaker was placed at the second floor of this house, on the top of the main stairway over a sheet of plywood and secured in place by planks of wood that were fastened to the plywood and squeezed between the walls to provide maximum force transfer to the building. The intent was to avoid any damage to the building, so the assembly was not bolted to the floor. See Fig. 3 for picture of test site, Fig. 4 for shaker setup, and Fig. 5 for channel locations.

Figure 3. 2-Story House (Pasadena)

Figure 4. Experimental setup.

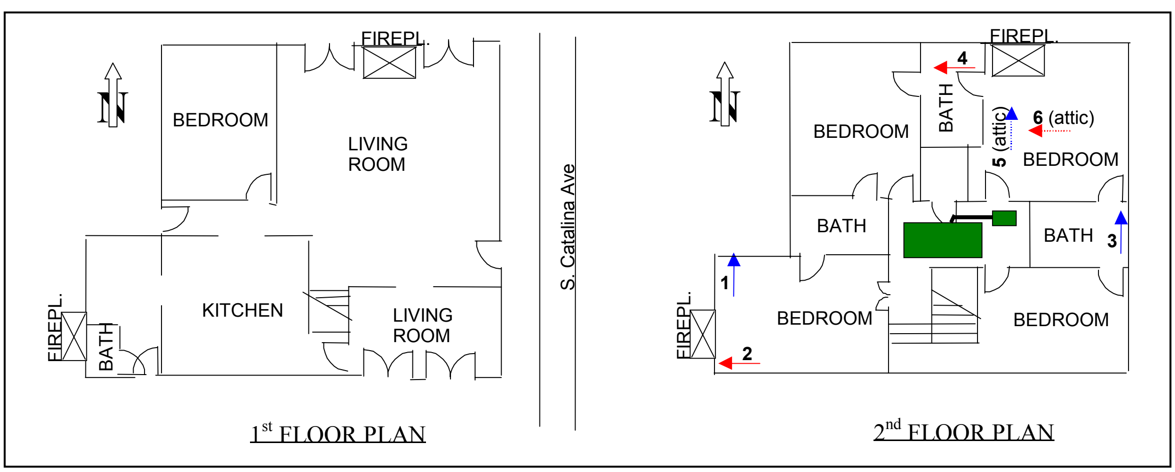

Figure 5. Seismometer locations

A set of frequency response curves is shown in Fig. 6 for shaker force oriented in the EW direction. The EW and NS fundamental modes of the 2-story house are coupled to the torsional response; all channels are excited in both modes as observed from the double peaks, one at each resonant frequency. The identified EW and NS fundamental frequencies are 5.5 Hz and 5.7 Hz at 2.5% eccentricity. Also, note from the figure the downward shift in fundamental frequencies as the eccentricity increases (larger shaker force). Maximum total drift was 0.54 mm for EW shaking at 20% eccentricity.

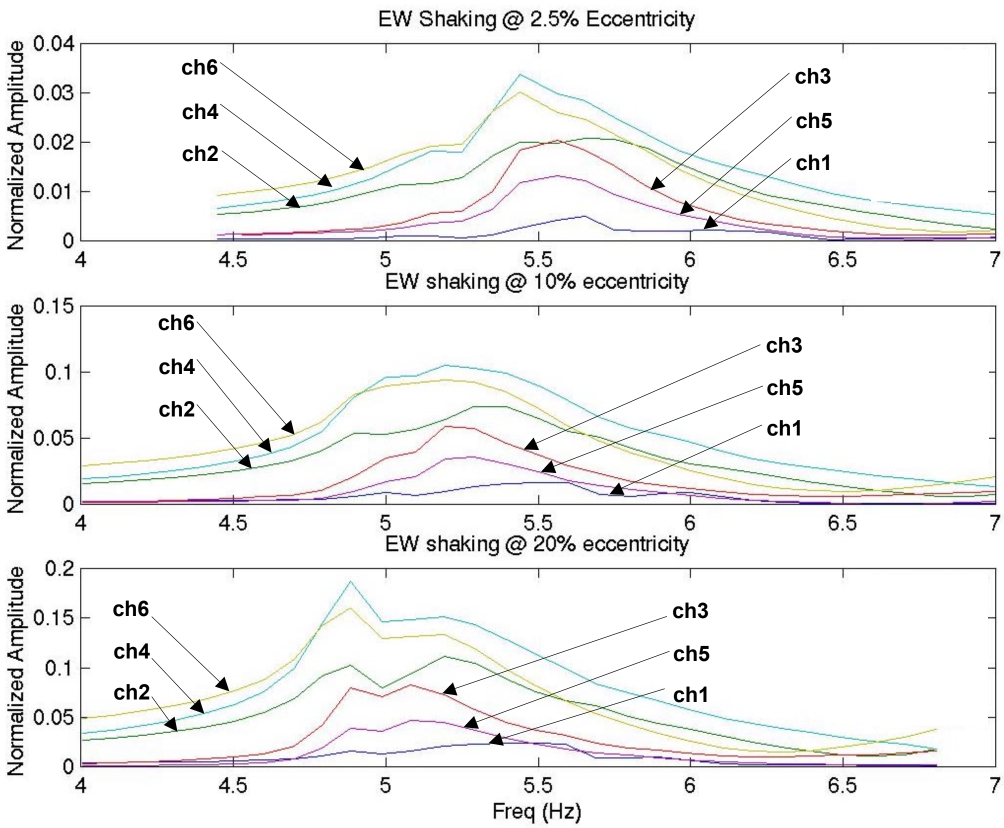

Figure 6. 2-Story House (Pasadena): Forced vibration tests on 6/27/00. The amplitudes are normalized by the square of the frequency. Odd numbered channels face North and even numbered channels face West.

3-Story Apartment Building (Pasadena)

This apartment building is owned by the California Institute of Technology and is located in the vicinity of the campus. It was built circa 1960, and it is currently being used as graduate student apartments. There is a partially underground parking garage with concrete block walls around three sides and the East side of the garage is open. The first floor plan area is approximately 5000 square feet, with an aspect ratio of approximately 3:1. The student apartments are located at the first and second floor levels, and there is a penthouse apartment occupying the third floor. The exterior wall finish is stucco, the interior finish is drywall, and the flooring is a soundproofing topping (probably lightweight concrete) over sheathing. The shaker was placed at the third floor, over a sheet of plywood and wedged between wood planks. Screws were driven through the planks, plywood and floor deck below to secure the shaker assembly. See Fig. 7 for picture of test site, Fig. 8 for shaker setup, and Fig. 9 for channel locations.

Figure 7. 3-Story Apt. Bldg. (Pasadena)

Figure 8. Experimental setup.

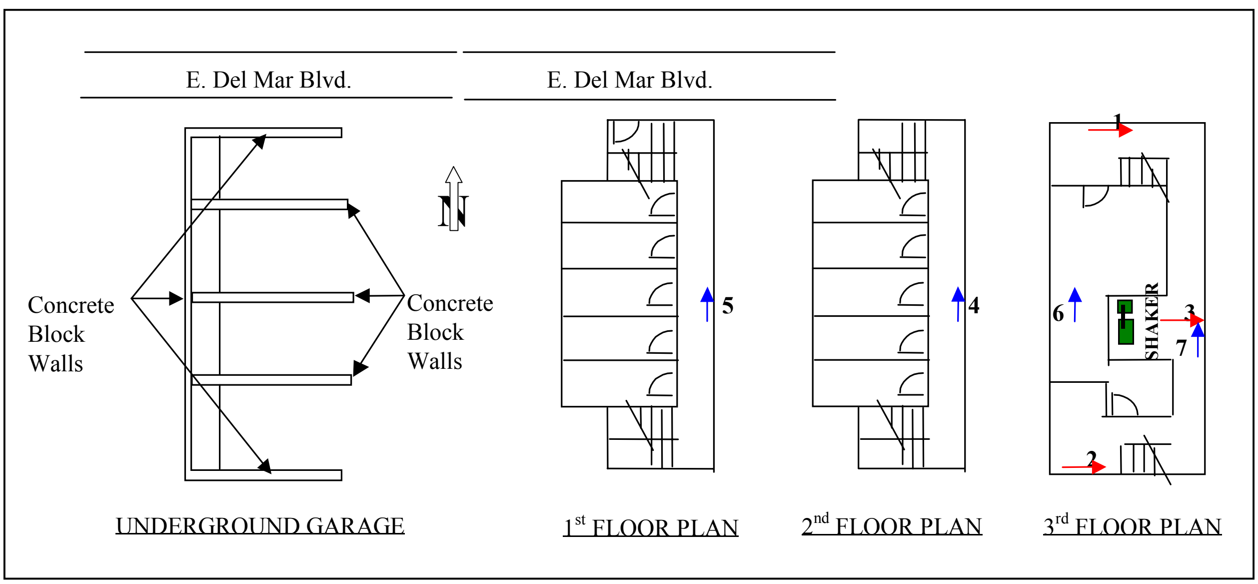

Figure 9. Seismometer locations.

A set of frequency response curves is shown in Fig. 10 for the shaker force oriented in the NS direction. The 3-story apartment building showed strong torsional behavior when shaken in this direction due to the lack of walls on the East side of the parking garage. The average NS motion amplitude (channels N6 and N7) at resonance is similar to the EW motion amplitude at the ends of the building (channels E1 and E2, which are out of phase). The identified fundamental resonant frequency is 5.3 Hz at 2.5% eccentricity; the value for EW shaking is 4.5 Hz (results not shown). Note from the figure that the fundamental frequency of this building decreased as the shaking amplitude increased. Maximum total drift was 0.52 mm for NS shaking at 20% eccentricity.

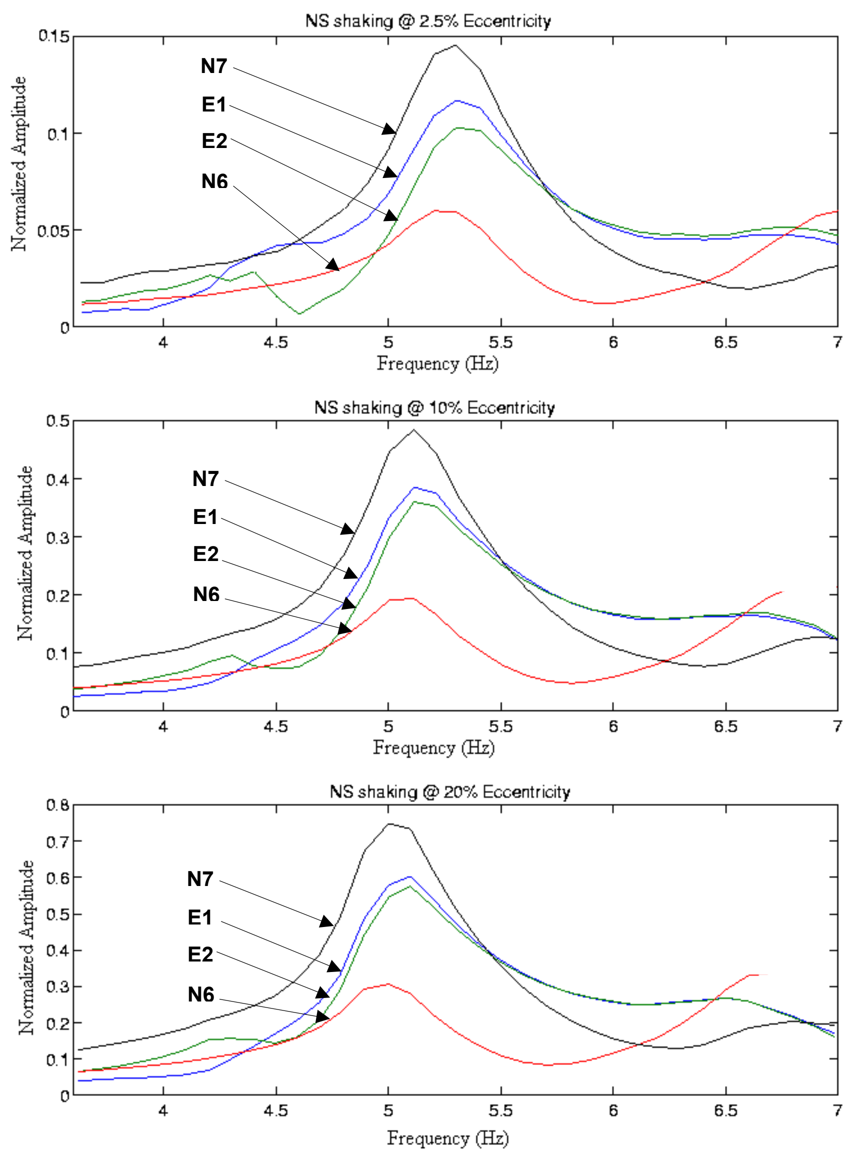

Figure 10. 3-Story Apartment Building (Pasadena): Forced vibration tests on 7/10/00. Amplitudes normalized by the square of the frequency.

Period Formula by Regression

The data obtained from the analysis of the earthquake records and the forced vibration tests was used to perform a regression analysis for the periods with respect to the height of the buildings. A Maximum Likelihood estimation method was chosen based on a lognormal probability distribution for the periods at each value of the selected regressor. The best-fit curve for the median period $\hat{T}$ can be represented by the following formula:

$$\hat{T} = 0.032h^{0.55} \tag{1}$$

where h is the height of the building.

Fig. 11 shows a comparison between the periods found from regression on data and the period formula prescribed by the 1997 UBC. The 16- and 84-percentile curves are also shown, where the standard error in lnT is 0.129 (Camelo, Beck and Hall 2001).

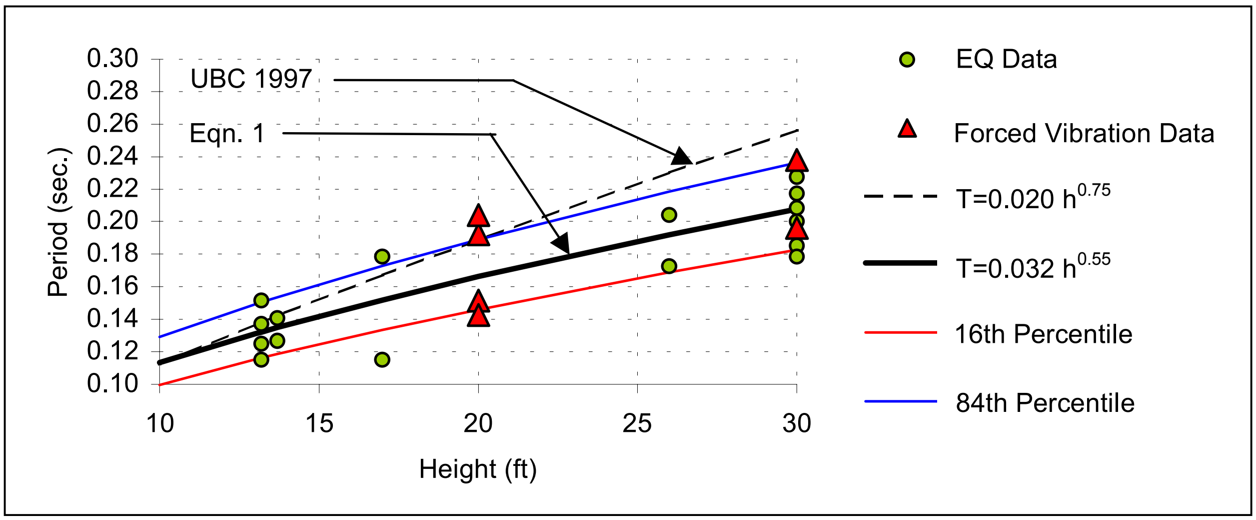

Figure 11. Period by Regression vs. 1997 UBC Period Formula.

Conclusions

The database compiled during this research has provided valuable insight regarding the dynamic characteristics of woodframe buildings, which showed fundamental natural periods between 0.11 and 0.24 sec (4.2 and 8.7 Hz), and damping ratios averaging 7.2% and ranging from 2.9 to 17.3%. This database was used to develop a period formula that can be compared to the current UBC formula, but it must be noted that the database was derived from low-amplitude shaking (inter-story drifts less than 1.5 mm), since strong shaking data is not currently available. The periods are expected to be significantly longer for stronger shaking of these structures, as suggested by the frequency shortening shown in Figs. 6 and 10. It should be noted that the damping values obtained from the forced vibration tests were much lower than those obtained from the analysis of the earthquake data even though the drift levels were similar. This may be due to differences between the buildings being tested and those from which the earthquake records were obtained, but at this time the cause of this variation is not clear.

The authors are currently testing other woodframe buildings to examine the effect of increased motion amplitude on the building's natural frequencies and to investigate the floor diaphragm behavior of these structures. These future studies are expected to assist in establishing sound design and construction guidelines.

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